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Nondestructive Evaluation and Inspection Programs for Pershing II Motors

by
Robert B. Moler
Frank W. Kearney
Mark D. Ginsberg

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The study recommended modification of existing inspection procedures and installation of an advanced RTR system, including a modification of motor-handling equipment. The existing betatron appeared to be a suitable X-ray source. Also recommended were a borescope, to inspect aspects of the solid fuel, and a thickness gage.

CT was rejected because it cost more than RTR without increasing inspection capabilities and would require extensive modification or replacement of existing facilities. Although potentially useful, advanced ultrasound methods are still at the experimental stage and could not be recommended. However, an advanced thermography system was found to be immediately applicable for detecting subsurface anomalies.

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Robert B. Moler, Frank W. Kearney, and Mark D. Ginsberg

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FOREWORD

This study was performed in support of the U.S. Army Missile Command (MICOM) Quality Assurance Directorate for the Pershing II Project, which provided funding through an interagency transfer under Project RD7P69MS57, "Nondestructive Evaluation for Pershing II." Mr. John Sweitzer was the Technical Monitor for MICOM.

This work was performed by the Engineering and Materials Division (EM) of the U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. Paul Howdyshell is Acting Chief of USACERL-EM. Robert B. Moler is President of Systems Support, Inc., Catharprin, VA.

LTC E.J. Grabert, Jr. is Commander of USACERL and Dr. L.R. Shaffer is Director.

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NONDESTRUCTIVE EVALUATION AND INSPECTION PROGRAMS FOR PERSHING II MOTORS

1 INTRODUCTION

Background

Historically, quality control inspection and evaluation of Pershing II (P-II) solid propellant rocket motors has been performed at the factory. The Army's job has been to review the manufacturer's results before delivery and to perform limited confirmatory testing. But no nondestructive evaluation and inspection had been designed that would be suitable for motors returned from the field.

Motors are now being removed from the field as part of an ongoing program of replacement. These motors have been subjected to stresses of transportation, assembly, and disassembly (sometimes many times) in addition to several years of local environmental stresses. The U.S. Army Pueblo Depot Activity radiographic facility has been given the responsibility for reinspecting these motors, which are to be used in an ongoing testing program. At present, PDA does not have the capability to perform satisfactory and efficient NDE/NDI of field-returned P-II motors. The U.S. Army Missile Command (MICOM) requested that the U.S. Army Construction Engineering Research Laboratory make recommendations for upgrading PDA's NDE/NDI quality assurance capability.

Objective

The objective of this study was to provide analysis and documentation for upgrading the capability of the PDA inspection facility to perform NDE/NDI reinspection and recertification of field-returned P-II motors.

Approach

The assessment was carried out in the following steps:

1. Inspect and evaluate PDA's inspection facilities and procedures.

2. Identify the inspection requirements of P-II rocket motors that have been returned from the field.

3. Identify and evaluate advanced technologies applicable to NDE/NDI for field-returned P-II motors.

4. Evaluate experimental technologies for potential application to P-II NDE/NDI.

5. Draft specifications for upgraded NDE/NDI procedures and equipment.

Two other tasks were anticipated to be accomplished as needed. These were (1) to provide independent review of radiographic inspections carried out on P-II motors in which there was some question regarding interpretation of observations or a question of the flightworthiness of the motor, and (2) to provide recommendations of the inspection type to be carried out on certain developmental motors. However, no significant inspection issues arose during this program, and the development program was limited to the production and flight test of a single motor. Consequently, the effort allocated for these tasks was redirected toward the principal objective of the research.

Mode of Technology Transfer

Technology identified as desirable for use with the P-II system was transferred to MICOM via specifications for new test procedures and specifications used to procure new test equipment. All of these specifications are included as the appendices of this report. As this report is being prepared, all new inspection procedures have been implemented at MICOM. Specifications for equipment have been set aside pending the outcome of current Intermediate Nuclear Force treaty negotiations.

2 PDA FACILITIES AND PROCEDURES REVIEW

The initial effort on this project consisted of a thorough inspection, review, and analysis of the facilities and capabilities for NDE/NDI at Pueblo Depot Activity. The initial inspection revealed a number of limitations in the plant facilities themselves. These consisted of limited physical size of the main radiography area so that the distance between the betatron source and the motor is a maximum of about 4 m. The beam stop behind the motor location is about 1.5 m away. The wall thickness is insufficient to achieve the external dose reduction required if a high-powered X-ray source such as a Linatron* were to be used. The entrance to the X-ray bay is such that motors must be brought in horizontally.

The existing motor-handling equipment uses a rubber belt sling arrangement to rotate the motors while in the horizontal position, a totally unsuitable and potentially dangerous method that is likely to cause severe damage to motors returned from the field.

The betatron provides adequate flux to achieve excellent film radiography, but it is very old and replacement parts are becoming scarce. It could be replaced by a Linatron 200AR with little effort, but it is highly reliable and has certain technical attributes that make it worthwhile to continue using it as long as it functions successfully. The very small source size (0.2 mm) is a great advantage in the limited space available in the radiography bay.

This inspection and analysis led to a recommendation to MICOM regarding the level of inspection of returned motors that should be carried out routinely in the interim before the principal facilities can be upgraded. These recommendations were formalized as standing operating procedures for inspection of P-II motors returned from the field (Appendix A).

* The Linatron series is manufactured by Varian Corporation.

3 PERSHING II INSPECTION REQUIREMENTS

Inspection requirements fall into two categories: (1) those mandated by MICOM or PDA or (2) those determined to be necessary based on experience, experimental evidence, or calculational evidence. In the first category are a number of inspection procedures that were instituted as part of the early development and production of P-II motors before there was much experience in their operation. For example, factory inspections include film radiography of areas thought to be critical and a general survey of the motor using a relatively crude system of RTR. Inspection requirements of the second type, those resulting from various tests, accidents, general experience with this and similar motors, and theoretical analysis of the P-II motor's response to thermal stress, are discussed in the remainder of this chapter.

There is general agreement that the most serious and perhaps most prevalent type of failure is caused by a separation of the fuel from the liner. Such a separation can lead to fuel burning in direct contact with the liner. A likely consequence is a rapid burnthrough and catastrophic failure. Failures of this type have occurred on several occasions with other solid rocket motors, although not with the P-II. It is the consensus of researchers that an unbonded area of 15 cm 2 and a separation of 0.38 mm potentially could lead to failure if it occurred in a critical region.

The case of a solid rocket motor must contain very high pressures during the brief period (usually less than 2 minutes) of operation. These cases, considered as pressure vessels, are designed with very small safety margins, usually about 25 percent. Consequently, the integrity and uniformity of the case must be quite high. External damage to the case that results in the loss of strength could lead to failure. Analysis is very complex because of the shape, method of manufacture, and temperature effects, but damage in a critical region that leads to a hoop tensile strength reduction of 30 percent in a region of about 20 cm^2 is thought to be significant. No meaningful criterion for the impact forces necessary to create such damage has been developed.

The development of cracks in the inner bore of the propellant can lead to breakup of the fuel and failure by several mechanisms. These cracks can result from extreme temperature stress (cold soaking to well below 0 °C) and potentially from aging of the fuel in conjunction with exposure to moderately low temperature. The cracks are very small, on the order of 0.025 mm, and difficult to detect. The only practical means of detecting such cracks is with the aid of a high resolution optical borescope. The characteristics of borescopes will be discussed in a later section.

Metallic inclusions in the fuel or in any of the spaces adjacent to the nozzle are highly undesirable. Ejection of an object in the fuel could damage the exit nozzle. A foreign object in the space adjacent to the nozzle could result in jamming of the nozzle and loss of thrust vector control.

During curing, the fuel shrinks. This shrinkage is accommodated by a dome-shaped rubber flap that is not bonded to the case at the dome ends. After the fuel is completely cured, this rubber flap, bonded to the fuel, may be separated from the case by as much as a centimeter. At the location where this rubber section is joined to the cylindrical portion of the liner, a critical flap bond occurs. If this bond is not sound, during fuel loading fuel can leak into the space between the flap and the remainder of the cylinder part of the liner. Ignition of this fuel could result in motor failure.

In most of the P-II motors, the liner is constructed of three cylindrical sections joined together at two locations with a "belly band." The band has a smaller diameter than the main sections of liner which overlap the band and are bonded to it. The main sections are butted together. These two joints have

received significant attention, although there are no known instances of a serious problem as a result of a fault in these joints. Nevertheless, inspection of the joint regions for integrity is considered important. The manufacturing procedures have been modified recently so that the joints are eliminated in favor of a single integral liner.

During the facility review, the need for an ultrasonic thickness gage was expressed by personnel at MICOM, and the particular uses to which it would be put were explored. It was concluded that several specific items integral to the motor require verification of manufacturing tolerance to within about 0.05 mm.

4 RECOMMENDED INSPECTION SYSTEMS

Digital Radiography

A substantial effort was devoted to reviewing various digital radiographic inspection procedures. The two most capable methods are computed tomography and digital cineradiography (real-time radiography).

Computed Tomography

It is clear that computed tomography (CT) offers the most advanced capability. It can quantitatively determine density variations smaller than 0.1 percent in a volume smaller than 0.01 em 3. There is no question that the smallest fuel/liner separations can be detected, and the ability to detect and locate inclusions or voids in the propellant is unsurpassed. CT can achieve essentially 100 percent inspection of an object as large as the 127 cm diameter P-II motor. Also, the presence of fuel behind the flap bond is likely to be readily detectable.

Nevertheless, there are several limitations to CT application for P-II inspection. The principal objection is the time required for complete inspection. Present operating units require between 20 and 30 minutes to collect and reconstruct a single cross-sectional image. This is roughly comparable to the time taken to make two film exposures; however, each such exposure would inspect a section only about 2 cm in vertical extent. Using film radiography with exposures taken every 15 degrees, each covering a vertical extent of 15 in., inspection of the critical regions requires about 12 hours of inspection time. Achieving the same result with CT would require about 15 hours. If 1-cm vertical increments were used, the time would increase to 30 hours. Analysis tended to support the conclusion that the additional capability of a CT system would not be used effectively for either the P-II or other items that might require inspection. Other limitations are its inability to detect the small cracks in the inner bore of the fuel and impact damage to the case. It is possible, however, that both of these limitations could be overcome by rapid advances in CT technology. In fact, significant progress is being made in ending the speed limitation.

Although CT systems are in development that could reduce the single exposure data collection and image reconstruction time to as little as 5 minutes,[1] this capability has yet to be demonstrated in a prototype or experimental system suitable for large rocket motor inspection. (It has been demonstrated for medical applications, which are much less demanding of X-ray beam energy and flux.)

Another characteristic of CT systems that mitigates against their use for P-II inspection is their limited resolving capability. In general, the high spatial resolution required for the specific applications involved in P-II inspection can be achieved in CT only at the expense of a considerable increase in time to collect data at the highest resolution of which the machine is capable. This large data set in turn results in a much longer reconstruction time. Morcover, the time given above (5 minutes) for single image data collection and reconstruction was not for the best achievable resolution in present systems but for

[1] Robert Armisted, private communication with R. B. Moler, June 1987. Mr. Armisted is president of ARACOR, Inc., Sunnyvale, CA.

developmental systems not expected to become operational for several years. It seems clear that the required capability will be achieved eventually, but most likely well after the need for P-II inspection has passed.

All of the CT systems rely on the very large output of a linac X-ray source. These X-ray sources produce a 15 MeV X-ray output in excess of 6000 R/min at 1 from the source target. The walls of the PDA physical plant are not thick enough to accommodate this source intensity. Consequently, either an entirely new building would have to be constructed or the primary shield wall would have to be approximately doubled in thickness. Either of these two expedients would result in a substantial delay in achieving the desired inspection capability.

Real-Time Radiography

Real-time radiography (RTR) has enjoyed considerable success in industry. While it cannot achieve some of the more spectacular accomplishments of CT, it provides high-quality routine inspections using modest X-ray sources and ancillary mechanical equipment. In the usual arrangement, an object rotates on a platform and a shadowgram developed on a fluorescent screen viewed by a television camera is displayed on a monitor. In order to detect fuel/liner separations, the system is optimized for tangential radiography by source collimation and other means. Separations as small as 0.025 cm can be detected if the separation extends circumferentially by about 3 em (an angular extent of 2.7 degrees). These images can be stored and manipulated in various ways to enhance the detectability of features in the image. In most systems the image storage is by analog videotape, a serious shortcoming for subsequent review or enhancement. Because of the storage medium limitations, efficient use of the procedure demands immediate review of the image presented on the screen.

One of the major advantages of the RTR system is its high spatial resolution capability. Because spatial resolution and contrast sensitivity are closely intertwined, it is not easy to compare CT to RTR directly. A CT system could have a contrast sensitivity of 16,000 (14 bits) compared to 256 (8 bits) for a typical RTR system. On the other hand, a good RTR system could have a spatial resolution of 0.25 mm whereas a CT system normally is limited to a resolution of 1 mm or larger. Because of inherent noise, ordinarily the high-contrast capability of a CT system cannot be used to full advantage, and for many applications the RTR system will be able to detect features not detectable by a CT system.

A preliminary conclusion in favor of an RTR system was made based on these and other considerations such as cost and the known extended delivery schedule of the Linatron required for CT systems. A decision was made to analyze the capability of the most advanced RTR system, with emphasis on determining whether such a system could achieve the inspection requirement appropriate to radiographic systems and whether it could do so using the betatron X-ray source.

The first step in this process was taken by defining many of the specific inspection requirements and facility limitations that would impact the kind of equipment needed to achieve these requirements. The basic theory used in image noise reduction, the output of the betatron, the efficiency of fluorescent screens and image tubes, and other parameters have been used to develop preliminary equipment performance specifications for inspection. The most serious limitation encountered was the available output of the 25 MeV betatron. This unit is rated as having an output of 200 rd/min at 1 m from the source. The spectrum from the betatron is essentially that of an ideal thin-target bremsstrahlung source; that is, the number of photons having a frequency between λ and $\lambda + \sigma\lambda$ is a constant for all values of λ. From this relationship it is possible to compare the total output of a high-intensity thick-target source such as a Linatron with the thin target source of a betatron. These calculations indicate that the output

of the betatron above 10 MeV is about 80 rd whereas the Linatron, with a total output of 6000 rd/min, has an output of only 320 rd/min for energy above 10 MeV. Thus the betatron is at a disadvantage of about a factor of 4 compared to the most intense available source. This conclusion is somewhat optimistic because the energy below MeV is significant even though the attenuation through the motor case is becoming very large. In the CT system, radiation must penetrate the fuel and case to be recorded by the detectors. This makes analysis of the effective intensity very complex. More detailed analysis suggests that the above analysis is probably correct within a factor of 2.

Rather than attempt to carry out a full analysis, a simpler expedient was used based on an analysis of the exposure parameters used for standard X-ray film radiographs. Linatron 6000 data for both film exposure and RTR exposure for a similar motor* were available. For the same film type and lead screen thickness as used for the P-II, but with the Linatron at a distance of 3 m instead of 2 m, the same film density was achieved with an exposure of 30 seconds compared to 2 minutes using the betatron. This ratio is a factor of about 8 in apparent intensity. A factor of 8 was used in subsequent analysis.

Standard industrial RTR systems operate on the basis of a framing rate (the time between successive scans of the stored image) of 1/30 second, the same framing rate used in standard television cameras. To increase the signal-to-noise ratio, successively digitized frames are averaged using an exponential averaging algorithm that permits good noise reduction without the need for large amounts of memory. In this scheme the number of frames that are averaged can be increased by powers of 2 up to 512 or even higher. But for tangential radiography of motors, the motors are rotated continuously at rates of a few degrees per second, and averages of more than about 256 frames lead to unacceptable image smearing. Both the frame rate and the averaging would have to be modified in order to achieve an adequate signal to noise ratio.

In addition to the source intensity limitations that would have to be overcome, the system would have to overcome a second limitation that exists with all commercial RTR systems. This limitation is the result of the eight-bit digitization that is standard for these systems. Eight-bit digitization imposes a limit of 256 levels of gray on the contrast achievable by the system, i.e., a contrast resolution (sensitivity) of 0.4 percent. By comparison, CT systems digitize to 16 bits and routinely operate with a contrast sensitivity range of 16,000, although the statistically significant contrast resolution usually is not better than 0.05 percent. It was considered desirable that an RTR system have a true contrast resolution of at least 0.1 percent (equivalent to digitization to 10 bits) and, consequently, the analog-to-digital system probably ought to be 12 bits, even though the last 2 bits might not be statistically meaningful.

The intensity limitation of the betatron potentially could be overcome by integrating on the photocathode of the image tube for a period longer than the standard 1/30 second. To do so would mean that other aspects of the system would have to be modified. Of particular importance would be reducing the inherent noise as well as the charge spreading that occurs because the photocathode is at room temperature. This is easily accomplished by cooling the photocathode, which is already a common practice, and the required cooling is easily achieved using thermoelectric cooling. It is then a trivial matter to change to a slow scan rate in the camera to take advantage of the ability to integrate for a longer period of time. Prototype and developmental RTR systems have already been modified to operate at 7.5 frames per second, and still slower rates could be accommodated. At this rate, the intensity limitation has already been largely removed.

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* The IUS motor, which is used to launch payloads from the shuttle into geosynchronous orbit, develops thermal gradients as high as those experienced by the P-II.

To achieve the desired contrast resolution, it is apparent that a large number of frames would have to be averaged. An approximate analysis based on the known noise level of a cooled photocathode in conjunction with the integrated intensity achieved with the betatron suggested that at least 32 frames would have to be averaged to achieve a contrast resolution of 0.1 percent, which would require a time of 4.2 seconds. (Using a Linatron and 1/30 second framing, 16 frame averaging is fairly typical.) Obviously, continuous rotation would not function in this circumstance, and a stopped-motion arrangement would have to be employed. In this arrangement, complete circumferential coverage would be achieved in 9.4 minutes using angular increments of 3 degrees (3.3 em along the circumference.) Once the question of whether there is sufficient intensity from the betatron to achieve the required contrast resolution in a practical system is affirmatively resolved, specifying the remainder of the RTR system parameters becomes relatively simple. Most of these parameters are designed to ensure that the system achieves high-quality images and does not produce artifacts that would make image interpretation ambiguous. Such items as blooming, resolution, uniformity of image field, and the remainder of the specifications given in Appendix B provide this assurance and make it possible to carry out quantitative image analyses with minimum manipulation of data. A number of other features, such as digital storage of the images and various advanced image analysis capabilities, were included in the system specifications, but these would have been a natural part of any system.

Facility Modifications

Some of the physical limitations of the way the motors presently are handled in the facility have already been discussed. Several of the existing methods clearly have to be changed not only to eliminate the potential for damaging motors but also in the interest of more efficient use of an RTR system. The most immediate problem concerns the method employed to rotate the motors. Current practice involves a pair of belts on which the motors are suspended horizontally. The belts are driven at low speed by a motor, but the presence of various external appurtenances on the motor necessitates the manual insertion of rubber pads with various cutouts designed to accommodate the external devices without crushing them. Rotation of the motors with this system is not smooth, especially when a pad is inserted. The motor tends to ride up the side of the belt opposite the pad and roll suddenly back to the center position. The operation is clearly undesirable in general and would make it nearly impossible to achieve the positioning accuracy desired for the RTR system. All present RTR systems operate with the motors in a vertical position and with rotation about the vertical axis. This arrangement minimizes stress on the motor. For the P-II motors, an alternative arrangement is used for some operations. This alternative is to hold the motors by the fore and aft steel rings, with no part of the body in contact with any rotation mechanism. These rings are not part of the motor and would have to be mounted on the motors each time inspection using RTR is called for. The vertical arrangement was considered to be the easiest to implement and would minimize manipulation of the motors.

Unfortunately, the facility entrance is not high enough to permit entry of the motors in the vertical configuration. They must be brought in horizontally and then erected. This will entail the installation of two additional cranes within the facility. It is possible to rotate the motors from horizontal to vertical with a single crane, but the operation would be less secure.

The present facility uses small rail cars both for transport and for the rotation mechanism. Use of the rail cars and rails would be retained; however, the car that presently has the rotation mechanism mounted on it would be cannibalized and a rotating turntable would be mounted on it. The turntable would operate in discrete steps, would have an accurate indexing mechanism, and would be able to accelerate the motors to maximum angular speed in about 0.5 second, a torque too small to pose a problem for the motors.

Because of the height of the motors, the betatron and RTR camera system must have a vertical motion of nearly 4 m while maintaining good alignment. The betatron mount already has this capability, but it must be coupled with a camera system that tracks it with the required precision. A laser alignment system can accomplish the required task in a straightforward manner and has been called out in the RTR specification of Appendix B.

Borescopes

It was noted that the PDA inspection facility lacked the ability to satisfactorily inspect the inner bore of the motors, a capability that is mandated by both MICOM and PDA. On those occasions when such an inspection was undertaken, it was performed using an obsolete borescope provided by MICOM. The characteristics of this unit were such that its real usefulness was highly questionable. A new unit was considered an immediate requirement.

Preliminary requirements for this equipment were developed based on the size of cracks that had been observed in a single motor that had undergone cooling to very low temperatures and the capability of state-of-the art borescope systems. The most capable such system requires that power be supplied to the viewing head so it can be manipulated, and so its focal length and magnification can be adjusted remotely. A high-intensity light at the head is another common feature that requires power.

Although it was clear that power could be safely supplied to the viewing head, existing safety requirements precluded electrical power within the bore of the motor. Although this prohibition could be eliminated, it would require a lengthy process of justification and safety assurance. Because the minimum requirements could be met without the need for electrical power at the bead, in consultation with MICOM it was decided to develop borescope specifications that did not include power to the head.

A survey of industrial borescope manufacturers was conducted, and the capability and I limitations of existing units were explored. It was clear that no off-the-shelf unit was available, but several units nearly matched the requirements. A meeting was held at MICOM with personnel from Systems Support (G. Fuller), MICOM personnel (J. Switzer and others), and several manufacturers' representatives. During this meeting details of the inspection requirements were explored and defined. The manufacturers were given an opportunity to inspect actual sections from a P-II motor and to examine the critical regions.

Following this meeting equipment specifications were developed based on the established and agreed upon inspection requirements and limitations. Some of the limitations (e.g., the restriction that electrical power would not be permitted in the motor bore) had a significant impact on the capability of any system that existed as a standard production unit.

The technical specifications that emerged were developed in consultation with cognizant technical personnel at MICOM. Light for illumination of the interior of the bore is supplied by a light pipe. A fiber optics system transmits the image to a camera head located outside the motor. To minimize light loss and provide easy access to the most critical areas of the motor, access to both ends of the motor was specified even though this would require removal of the igniter at the forward end. Because manipulation of the fiber optics system would be entirely mechanical and no change in focal length would be possible, detailed examination of the most remote parts of the P-groove would not be possible. These specifications could be achieved with modest adaptations of existing equipment and would fulfill the inspection requirements, but with some limitations of capability.

The specifications were translated into a statement of work for inclusion in a request for quotation. Documentation is provided in Appendix C.

Thickness Gaging

A second area of concern that emerged during the initial review visit to PDA was the need to carry out thickness gaging on a number of parts. Although these measurements are not considered critical, they are carried out as a routine part of a complete inspection. In the past these measurements were made using an ultrasonic thickness gage on loan from a local agency. This instrument was no longer available.

The principal requirements for the thickness gage are that it be a simple band-held unit capable of measuring the thickness of aluminum and steel sheet as thin as approximately 0.5 mm, that it have a precision of 0.05 mm, and that it have the built-in capability for simple two-point calibration. A review of a sample of available commercial instruments made it clear that the requirements could be met easily with any number of units. Several units had built-in delays that allowed the gaging requirements to be met. In addition, a simple two-point automatic calibration was a common feature, and several of the simpler hand-held units provided this capability. Following a review of the requirements with MICOM and PDA personnel, complete specifications were developed for use in a procurement package. These specifications are the key features of a statement of work to be incorporated in a request for quotation. Complete documentation is provided in Appendix D.

5 REVIEW AND ANALYSIS OF OTHER ADVANCED INSPECTION METHODS

Numerous approaches to nondestructive examination and inspection have been developed and applied to a variety of composite materials and structures. One goal of this research was to determine which advanced inspection and evaluation procedures other than radiography could be successfully applied to the new materials being proposed and developed for the P-II program and to recommend whether these approaches should be incorporated in the PDA inspection facility. It would be impossible to examine all of these possibilities within the constraints of this project, but it is apparent that some of the more widely used techniques have greater potential than others.

In a recent conference on NDE of aerospace structures,[2] many of the more applicable available techniques were described, and practical applications of them were presented. It was clear that computed tomography, with its ability to visualize structural cross sections and quantitatively to measure material density in a small volume, had become the most sought after method and the one in which the greatest strides were being made in advanced developments. But CT continued to suffer from an inability to connect these observations with critical materials-related mechanical or thermomechanical properties.

Other radiographic procedures, including RTR, suffered from this same problem even though there bad been numerous studies intended to remedy this deficit for some specific material. Unfortunately, these studies were disappointing in that they did not result in the clear connection expected and sought.

Next to advanced radiography, ultrasound methods were most frequently applied to composite materials. But the ability to derive a useful connection between mechanical properties and ultrasound measurements was even less successful. Attempts to relate the intensity of the rear surface return signal in a pulse echo measurement to mechanical properties or to the density measurements made using CT were essentially a failure. No meaningful correlation was observed except for cases where impact damage had become so severe that the return signal was absent. Separations in the material sometimes resulted in an early signal that could be identified, but a consistent pattern did not emerge. These negative results were in contrast to the studies presented by Heyman.[3] In these studies, careful application of theory based on a phenomenological understanding of the interaction of sound with the materials, and an analysis of the fundamental characteristics of transducers led to the ability to relate velocity and attenuation to mechanical properties of interest in a quantitative way. These studies and results will be discussed in greater detail in the following section, Advanced Ultrasound Methods.

In addition to radiographic and ultrasound methods, thermal imaging methods are often considered, particularly where the composite material is expected to exhibit changes that will affect its thermal conductivity. Separations and changes in density that might result from impact damage are the most frequently cited examples.

Numerous simple experiments have illustrated that for graphite/epoxy or carbon/carbon composites, simply looking for obvious temperature differences caused by changes in conductivity will be unsuccessful. Nevertheless, it can be shown that because of the general uniformity of the materials, relatively small localized changes in material characteristics would result in real differences in heat flow.

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[2] *Nondestructive Evaluation for Aerospace Requirements Conference*, University of Alabama, August 26-27,1987.

[3] E. Heyman, "Quantitative NDE-Physical Models, Principles and Analysis," *Nondestructive Evaluation for Aerospace Requirements Conference*, University of Alabama, August 26-27, 1987.

The difficulty is in detecting and visualizing such changes without being overwhelmed by other random small changes. It is not sufficient simply to make the thermal image more sensitive, that is, to make it capable of resolving yet smaller temperature changes. A more basic approach must be taken. This approach is one that is being applied to imaging in a number of applications and involves the fundamental characteristics of image fields. In the examination of composites, it also involves anticipating the way heat would flow in a uniform (undamaged) material.

What is involved is an application of the Laplacian to the scaler field of temperatures. When this field is averaged using a Gaussian function to remove local variations, the Laplacian results in an extremely powerful way to locate nonrandom changes in the field. This approach will be reviewed and described, and its applicability to the P-II program discussed, under **Thermography**.

Advanced Ultrasound Methods

Ultrasound methods were developed for and have been most successfully applied to metals and other homogeneous materials. The methods in common use are relatively simple because they are intended to detect features such as voids and cracks that give rise to quite distinct features in the signals. Of course, the methods used for medical scanning are relatively more complex, but rely to a large extent on the fact that most features are much like an object in a water bath.

For composite materials, however, the situation is much different. The material itself is not homogeneous, and in most cases it is highly attenuating. Furthermore, variations in density are common. All of these variations affect the velocity and attenuation of the signal and make detection and interpretation of features quite difficult. Although these problems are inherent in the materials, they can be circumvented to a degree by proper application of the phenomenology of transmission and scattering of sound and the use of signal-processing methods to account for and remove the effects of the transducer on the signal. In combination, these approaches appear to enable ultrasound examinations that will allow quantitative evaluation of several important characteristics of composite materials.

These methods rely heavily on computer processing of the data. Consequently, it is necessary, as a first step, to digitize the signals to be recorded. This in itself is a departure from the usual practice, although it was proposed by Boeing for the IUS and used in one study.[4] Digitization is assumed in the following discussion.

Pulsed signals are commonly used in ultrasound. In the usual application a wideband transducer is pulsed, producing an impulse function. Detection of the delayed transmitted signal allows the determination of the velocity and attenuation of the material. A better signal-to-noise ratio can be attained if deconvolution of the transducer response is used to recover the original impulse.[5]

A superior approach is to use a narrow-band pulse train (tone burst) and measure the phase shift of the detected signal with respect to the original signal delayed by the appropriate amount.[6] (Alternatively, the delay or frequency is varied to keep the phase shift constant.) In this way small variations in the

[4] Boeing Corporation, *Ultrasonic and CT Scan Criteria for Carbon/Carbon Structures*, Boeing Special Study FSD 85-008 (Boeing, 1986).

[5] B.T. Smith, et al., "Correlation of the Deply Technique With the Ultrasonic Imaging of Impact Damage in Graphite/Epoxy Composites," submitted for publication in Materials Evaluation.

[6] J.E. Heyman, *Pulsed Phase Locked Loop Strain Monitor*, NASA Patent Disclosure LAR 12772-1 (1980).

velocity and attenuation can be determined with considerable precision. This approach requires that the thickness be known or that it remain constant. If an independent method of measuring thickness is available, then the technique has been shown to be able to detect important characteristics such as the presence of impact damage. Madaras, Poe and Heyman[7] demonstrated how these techniques could be used to quantify the reduction in tensile strength of a graphite/epoxy composite that had been damaged by impact at a level that produced no visible damage.

A further improvement to this method is achieved if the transducer response function is taken into account. Kishoni[8] has shown how to do so in a way that results in the smallest possible error in the deconvolved signal using a reference signal to calculate the coefficients of the discrete, finite-length convolution function. By narrowing the signal through this method of signal processing so that it approximates an impulse, features that would be difficult to detect by traditional methods are easily recognized and analyzed. Kishoni[9] used this method to observe the course of curing in an epoxy bond between a graphite matrix and a steel plate.

Most of the above techniques were applied using ultrasound frequencies above 1 MHz, where attenuation in graphite/epoxy and kevlar/epoxy composites is quite severe. To overcome the observed attenuation, large signals were applied. Only in the work of Kishoni[10] was the relatively low frequency of I MHz used to reduce the attenuation problem. Some studies[11] on the kevlar/epoxy material of the P-II case had emphasized the attenuation problem and pointed out the value of operating at lower frequencies. The major disadvantage of using lower frequencies is the poorer spatial resolution that must be accepted, but in all the areas of concern that have been considered and studied, the resolution achievable at frequencies as low as 100 kHz would be adequate.

A second problem that arises in the use of low frequency is the lack of suitable transducers. Most commercial transducers have been designed to operate in the frequency range well above 1 MHz because the most important applications have been in detecting flaws in metals where the high resolution is a necessity. Although some of these transducers can be modified to operate at lower frequencies, it would be better to design a new transducer optimized for operation at frequencies below 1 MHz.

There is a secondary advantage to operating at lower frequency when the signal is to be digitized—the analog to digital converter need not have the very high sampling rate required to digitize a 5 MHz tone burst. Of course, the lower frequency has significant impact on noise reduction as well, even though the narrow-band filter that can be used with a tone burst already results in a substantial improvement in the signal-to-noise ratio. In fact, it is this narrow bandwidth and the concomitant improvement in noise that allows practical operation at high frequencies in the face of severe attenuation of graphite/epoxy composites.

It is apparent that the most important advances in ultrasonics are in the approach to signal processing and in modeling the phenomena of transmission and attenuation of sound waves in composite materials.

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[7] E.I. Madaras, C.C. Poe, and J.S. Heyman, "Combining Fracture Mechanics and Ultrasonic NDE to Predict the Strength Remaining in Thick Composites Subjected to Low-Level Impact," *IEEE Ultrasonics Symposium*, November 17-19, 1986.

[8] D. Kishoni, "Application of Digital Pulse Shaping by Least Squares Method to Ultrasonic Signals in Composites," *Review of Progress in Quantitative NDE* (June 23-28, 1985).

[9] D. Kishoni.

[10] D. Kishoni.

[11] W. Clotfelter, *Nondestructive Assessment Methods for Pershing II Motors*, Northrop Services, Inc., Report TR 201-2077, U.S. Army Contract DAAH01-82-D-AOll (Northrop, June 1983).

The demonstration of the ability to quantitatively determine porosity,[12] delaminations,[13] and the reduction in tensile strength of impacted composite material[14] using ultrasonic methods indicates that major advances in the ability to carry out meaningful nondestructive examination of these materials are being achieved.

Further advances are likely in the near future, for example, the use of optimized low-frequency transducers that will make examination of very thick materials practical and routine; more efficient coupling means, such as soft wheels that provide efficient transmission of sound, particularly low-frequency sound; and efficient algorithms and fast computers that permit essentially on-line use of these powerful data analysis procedures.

Because these techniques are not yet available as commercial developments, it may not be appropriate for MICOM and PDA to procure such equipment at this time unless the risk attendant on sponsoring an advanced development is acceptable. Although the techniques have reached the laboratory demonstration stage, they have not reached the stage at which industry is willing to undertake prototype development and demonstration.

Thermography

The development of sensitive infrared detecting cameras and image intensifiers has led to the use of thermography as an important tool in a number of fields. Although not now an important method for medical applications, it was once thought to have significant potential for diagnostics. Thermography is used in a number of industrial applications where it enjoys some favor. Thermography has been promoted for use on composites, but in practice it has not proven to be as useful as anticipated.

Most thermographic systems rely on the simplest approaches. The object is heated, usually with an impulse source, and then viewed with an infrared-sensitive camera with a temperature resolution of a few tenths of a degree Kelvin. The thermal image is simply observed and any anomalies are noted. Some simple image enhancement procedures may be used, such as contrast windowing (the displayed contrast range is some part of the total recorded range). Attempts to observe delaminations and impact damage in carbon/carbon composites in this manner have been unsuccessful.

A much more powerful technique has been demonstrated by investigators at the National Aeronautics and Space Administration's (NASA) Langley Research Center.[15] This technique takes advantage of the nature of heat flow in a uniform medium as described by Laplace's equation. If a uniform medium is heated, the two-dimensional Laplacian will be zero at every point as a function of time. However, if the heat flow is not the same at every point, application of the Laplacian will result in a nonzero field that will vary with time. In essence the Laplacian is a two-dimensional second derivative of the time-varying temperature.

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[12] M.S. Hughes, et al., "A Relationship Between Frequency Dependent Ultrasonic Attenuation and Porosity in Composite Laminates," *Review of Progress in Quantitative NDE* (June 21-26,1987).

[13] A.M. Buoncristiani, and Barry T. Smith, "Backscatter of Acoustic Signals From Inhomogeneities in Composites," *IEEE Ultrasonic Symposium*, October 16-18, 1985.

[14] E.I. Madaras et al.

[15] J.E. Heyman, private communication with R.B. Moler, February 1988. Mr. Heyman is a researcher at NASA's Langley Research Center, Hampton, VA.

In application, the technique could be very sensitive to surface irregularities or trivial variations in thermal conductivity. To avoid this type of effect it is necessary to use Gaussian smoothing and to normalize the results using the initial observations. Any subsurface changes in conductivity become obvious and can be related to delaminations, porosity, and impact damage.

This technique has become practical because microcomputers can carry out the requisite calculations very rapidly. Practical demands would require the ability to compute the Laplacian of the Gaussian of a scaler field of 200 x 200 points in about 1 second. This operation has become possible using the fastest available microcomputers and efficient algorithms. Thus, it does not pose a significant barrier to application of this approach, particularly when it is recognized that further speed improvements will occur in the near future. This level of resolution would make it possible to examine an area of 20 cm x 20 cm with a resolution of 1 mm. A spatial resolution of 2 to 3 mm is probably all that is required because the kind of defects that are being sought would have to be at least a few square centimeters in area to be significant. Even with 1 mm resolution, a complete scan of a P-II case could be done in less than 5 minutes. This estimate assumes that the thermal conductivity of the case is sufficiently large that anomalies far from the surface would be detectable at the surface within 1 second. If that is not the case, then a more complex system, possibly involving two cameras, would have to be used to reduce the time that would otherwise be lost while waiting for thermal effects to be manifested.

Existing infrared cameras and computers can be immediately employed to carry out this technique. Thus, it does not suffer from the development cycle that was identified with the more advanced forms of ultrasonics. Consequently, the most serious issue is the degree of applicability of the approach. Currently, very few data are available on specific applications and results. Additional information on a range of applications and the limitations encountered is needed before this approach is considered for general application. Nevertheless, it would be appropriate to begin this process with available equipment because it can be done with a relatively small commitment of resources.

6 CONCLUSIONS

The U.S. Army Pueblo Depot Activity radiographic facility was known to have a number of limitations for the efficiency and quality of inspection and evaluation of P-II motors. Review and analysis of the facility and the procedures being used confirmed the need for substantially upgrading the facility in both the quality of the NDE/NDI that could be carried out routinely and the efficiency with which the NDE/NDI function could be performed. The major requirement was achieving the capability of carrying out high quality radiographic inspection in an efficient manner that would allow essentially 100 percent inspection of all P-II motors being returned for flight recertification.

In general, it was concluded that the present method of radiography should be used with great care and only in those cases in which there was suspected damage based on direct visual inspection of the motor case or on the basis of documentation that the motor had been accidentally abused during handling or shipment.

The existing facility was found to have some limitations that would restrict the type of equipment that could be installed without major modifications. It was concluded, however, that if a digital real-time radiography system could meet the defined NDE/NDI requirements, the existing facility would be adequate, and the existing betatron would probably be a suitable X-ray source.

As part of the overall inspection procedures review and analysis, it was found that the existing procedures for carrying out radiographic examination of the P-II motors resulted in operations that had the potential for serious accidents. These safety problems were sufficiently severe to warrant the development of new procedures that would minimize the accident possibility while preserving the most important inspection goals.

On the basis of an extensive analysis it was concluded that for the routine and ongoing inspection and examination of P-II motors for the most prevalent and most important type of defects and damage, an advanced version of digital fluorescence cineradiography (real-time radiography, or RTR) would be the most efficient and cost-effective method available. Furthermore, it could use the existing betatron source and would require minimal changes to the existing physical plant. The salient features of the recommended RTR system involved noise reduction through a reduction in the framing rate of the camera, integration of multiple frames of a motionless motor, and a 12-bit digitization of the analog image in order to improve the contrast sensitivity of the system. In combination, these and other advanced features indicate that the existing betatron would provide sufficient X-ray flux for the system.

Careful analysis showed that such an advanced RTR system could detect virtually all of the conditions known to be, or suspected of being, capable of causing problems in the handling or operation of the motor. These conclusions were based on the implementation of a number of advanced features in the recommended RTR system that were not standard in commercial RTR systems, but had been demonstrated in prototype or one-of-a-kind commercial installations. It was concluded that the risk involved in achieving this type of system was not large and that there would be only a modest cost premium over acquiring a standard RTR system.

Two other systems were recommended for immediate acquisition and use. One, a borescope system, would fulfill a requirement for inspection of the inner bore and the p-groove in the solid fuel of the motor.

An ultrasonic thickness gage, although of lesser importance, was needed to measure the thickness of certain parts to verify compliance with manufacturing specifications.

Although computed tomography (CT) is technically more capable than RTR, this enhanced capability could not be effectively applied to identifiable requirements for P-II inspection and examination that were not already adequately addressed by the advanced RTR system. Additional factors that mitigated against the CT system were the very large increase in cost that would be entailed and the much longer time that would be necessary for system delivery and installation, and achievement of operational status. The higher system cost was exacerbated by the need to either extensively modify the existing physical plant or build an entirely new structure to house the system.

Other advanced inspection and evaluation techniques were found to have significant potential for application to the P-II. Advanced techniques in ultrasonics were the most important of these methods. They were capable of detecting features in the composite cases of the P-II that have long defied ready detection and evaluation, such as impact damage and other material defects that would result in decreased material strength. Although these advanced ultrasonic techniques have been demonstrated and prototype equipment has been developed, none of the ultrasonic methods had reached the stage of development that would allow immediate application. Thus, there are no commercial sources of the required instrumentation. Also, the digital signal processing that is a key element in these methods is not generally available and would require substantial effort for its adaptation for other computer systems. Despite the inherent attractiveness and considerable promise of the ultrasonic systems, their use in the PDA facility could not be recommended.

The other technique examined, a thermography system using a unique and advanced form of digital data analysis, was found to be immediately applicable despite a very limited base of experience in its use. Advances in computers have made it possible to carry out digital analyses of thermographic images in a way previously not considered. This approach, which makes use of the Laplacian to detect subtle changes in surface temperature caused by subsurface anomalies, can be immediately adopted using readily available commercial systems. Because these systems are relatively low cost) the additional costs of development of a base of experience in applications would be easily accommodated.

In conjunction with the advanced RTR system recommended, the equipment involved in the handling and manipulation of the motors was recommended for substantial upgrading to provide improved procedures and to eliminate a number of significant hazards of existing operations. These upgrades were integrated with the acquisition of the advanced RTR although they would be useful in their own right, particularly in mitigating the safety problems that had been identified. The most important of these facility upgrades is the use of a turntable that would allow the P-II motor to be inspected with its main axis vertical. This is the preferred orientation and the one generally used for RTR inspection. Because of restricted access to the radiographic facility at PDA, the motors must be brought in horizontally and then erected. In spite of the additional equipment (overhead cranes) needed and the added complexity of changing from horizontal to vertical orientation and back to enter and exit the facility, it was concluded that using a turntable to position motors for radiographic inspection provides a substantial improvement in safety as well as much better control over positioning the motor.

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APPENDIX A:

INTERIM INSPECTION PROCEDURES

Background

As part of a program to upgrade the Pueblo Depot Activity radiographic facility pursuant to the continuing need to re-inspect Pershing II motors that have been returned from the field and are to be used in an ongoing test program, a review of the existing facilities and procedures was carried out. As a result of this review it was concluded that the methods used to rotate the motors for the purpose of tangential radiography could lead to an accident with significant potential for either damaging the motor or resulting in personnel injury. Consequently it was concluded that this procedure should be used only in those instances where damage to a motor is strongly suspected or known to have occurred and tangential radiography would be the only practical method to assess the severity of the damage. Other inspection methods would be used to the maximum extent possible.

A revised set of procedures was devised to minimize the use of the hazardous procedures while providing an acceptable level of assurance of the flight worthiness of the motors being inspected. It was recommended that the facility be modified to allow the motors to be placed in the vertical position and that a turntable be installed to permit routine tangential radiography of the motors in the vertical position.

The following interim procedures were developed for use in the period until the improved motor handling equipment could be procured and installed.

Revised Inspection Procedures

This procedure is for the inspection of Pershing II stages returned from the field. The inspection will be carried out in the radiographic facilities of Pueblo Depot Activity, using the existing equipment following the procedures outlined below.

Because of the potential for accident and damage to the stages, use of the belt roller mechanism for routine radiographic inspection is to be kept to a minimum.

Detailed visual inspection will be the primary method of inspection for motor damage or abuse. This examination will be carried out as follows:

1) Using appropriate lighting to enhance surface features (a hand held high intensity lantern may be desirable) carefully examine the complete external pressure vessel surface, the skirts, and the accessible parts of the domes noting and marking any areas for further examination that have the following indications:

(a) Permanently depressed areas of a generally circular appearance indicative of a strong impact,

(b) Radial striations surrounding an area of surface crazing or paint flaking,

(c) Severe surface abrasion that begins more or less abruptly (one inch or less), extends in one direction, and declines rapidly in severity (one or two inches), indicating a glancing blow.

2) In those areas of a motor in which visual inspection or written reports indicate that the motor in question has undergone some mishandling, accident, or other abuse that could have led to damage, the motor shall be inspected by tangential radiography employing the following procedures:

(a) Optimum radiographs using cassettes double loaded with types "M" and "T" film or equivalent to achieve a minimum of 2T using a wire penetrometer in the vicinity of the case to liner interface.

(b) Using (a) above record radiographs every 6 degrees in the area of suspected damage.

(c) If either severe case damage (as indicated by large apparent separations or a depression of the liner) or separations between the case and liner or liner and propellant is observed, additional radiographs every 3 degrees will be recorded to define the extent of the damage.

Discussion of Surface Flaws

In a visual inspection procedure it is important to be able to distinguish ordinary surface blemishes that are an expected consequence of routine handling procedures and those surface features that might indicate a damaged condition. Motors and stages are subject to a variety of operations that will rub and abrade the surface. Many of these operations will result in minor surface abrasion, scratches and paint removal that extends in a circumferential pattern, particularly in the areas of the cradles used to support the stage and the slings used for lifting. Similar abrasion and scratching may be evident in other directions. Such appearances can be the result of sliding or shifting of a motor or other effects, but are not expected in normal handling. They should be examined to verify that they are not the result of impact damage.

APPENDIX B:

STATEMENT OF WORK/SPECIFICATIONS FOR REAL-TIME DIGITAL RADIOGRAPHIC INSPECTION SYSTEM

1.0 SCOPE

This specification describes the requirements of a Real-Time Digital radiographic inspection system required for the U.S. Army Pueblo Army Depot radiographic inspection facility to enhance the inspection of solid rocket motors. The Real-Time Radiographic (RTR) system is to be installed in an existing facility and shall function with the existing betatron high energy X-ray source. Solid rocket motor handling equipment will be required in conjunction with the RTR system.

2.0 APPLICABLE DOCUMENTS

Drawing 11503 519-089, sheets 2 and 3, 1st Stage Rocket Motor
Drawing 11503333-079, sheets 2 and 3, 2nd Stage Rocket Motor
U.S. Army Missile R and D Command, Redstone Arsenal, Alabama

Drawing of Facility Layout
U.S. Army Pueblo Depot Activity, Pueblo, Colorado

Specifications of the Betatron

Annex A: Significant Characteristic of Propellant, Liner, and Case for Pershing II Rocket Motors.

Annex B: Radiographic Procedures Used with the Betatron for Pershing II Film Radiography.

3.0 REQUIREMENTS

3.1 Real-Time Digital Radiography System

3.1.1 System Performance

3.1.1.1 *RTR Camera and Image Storage and Manipulation.* The system performance requirements defined in the following paragraphs shall be met.

Resolution - The first zero crossing of the Modulation Transfer Function shall be greater than or equal to 2 line pairs per millimeter for a 10 by 10 cm field of view at the motor measured with a high contrast bar test object.

Contrast Resolution and/or Sensitivity - It is intended that the system contrast resolution be compatible with a sensitivity of 0.5 % 2T, based on the Betatron output and using up to 512 frames of frame integration for the 10 cm by 10 cm field of view. Contrast resolution shall be achievable at both maximum and minimum attenuation using penetrometer with randomly oriented holes. Demonstration of the maximum attenuation contrast resolution capability shall be achieved using a twenty (20) centimeter thick nylon block penetrometer. The penetrometer shall have

flat-bottomed holes with depths of 1, 2, and 4 millimeters and diameters of 4 mm. Measurement of the average intensity of a 10 x 10 pixel array in the 1.0 mm hole shall exceed the average intensity on an adjacent 20 x 20 mm pixel array by an amount equal to or greater than 3 times the average pixel noise (3 standard deviations) of the 20 x 20 array. At minimum attenuation a nylon penetrometer of 2 cm thickness shall be used. It shall contain holes of depth 0.1, 0.2, and 0.4 mm and a diameter of 2 mm. The intensity within the smallest hole shall be measured using a 5 x 5 pixel array. The criterion for contrast resolution defined above shall be used.

Intra-Frame Dynamic Range - The single frame dynamic range of the system shall be such that the minimum to maximum thickness of the Pershing II motor shall be imaged without saturation or excessive noise. This performance shall be demonstrated either by:

1) Calculation based on the composition, density and thickness of the chord length through the case, liner and propellant of the motor with the motor, X-ray source and camera arranged so that no more than 2.5 cm of air will be displayed. (The region of air is not part of the specification.)

2) Use of a section of a motor supplied by MICOM: For test purposes the motor, X-ray source and camera will be arranged as described above.

Blooming - The 10% to 90% points of the minimum to maximum contrast achieved for a high-contrast test object shall be achieved over a distance of 2 mm or less referred to the 10 by 10 cm image plane at the motor.

Structure noise - Within the image of a uniform density object filling the 10 x 10 em field of view, no more than 250 pixels shall deviate from the image average signal of the field by more than plus or minus 5 times the average deviation (one sigma) of a single pixel from the image average of the field.

Magnification - The viewing area shall be selectable at either of two areas, either 10 by 10 em or 20 by 20 cm.

Archival storage of data - Optical disc storage of the "write once read many" (WORM) technology shall be used. Selection of images shall be by random access. Each disc shall have a minimum storage capacity of 100 megabytes.

Image enhancement - Edge enhancement and digital image subtraction shall be provided. Other techniques optional. The edge enhancement technique shall be specified.

Image presentation - Images shall be presented on a high resolution monitor including digital window and level control.

Linearity - For 1 cm 2 area averages in the image of a 20 cm thick nylon block, there shall be less than 1% grey level variations between the center and the periphery or between opposite edges for the 10 x 10 cm field of view. Up to 512 frames may be averaged for the final image.

3.1.1.2 *Turntable and Indexing.* The following performance requirements shall be met:

Step Size - The minimum angular step size shall be 1.5 degrees, plus or minus 0.25 degrees.

Rotation Speed - The turntable must be capable of advancing at the rate of I degree per second. Acceleration of 2 degrees/s^2 is desired. Rapid deceleration is desired in order to minimize the time between steps. A maximum settling time of 1 second is desired.

Accuracy of Repositioning - Repositioning of a motor during examination shall be accurate to within plus or minus 1.0 degrees in the angular direction and within plus or minus 1 cm in the vertical direction following an initial indexing of the motor. An indexing system shall be provided so that a motor may be repositioned to the above accuracy following re-installation of the motor on the turntable.

3.1.2 Design Specifications.

3.1.2.1 *Radiographic System*

Compatibility with Betatron - The Betatron shall be used as the source of high-energy X-rays. Account shall be taken of the source intensity (approximately 180 R/min at 1 meter) and source spot size (approximately 0.2 mm) to optimize the quality and system sensitivity. The Betatron output is characterized as being an ideal thin target bremsstrahlung spectrum.

Field of View - The field of view shall be selectable in either of two sizes; 10 by 10 cm or 20 by 20 em. All requirements and specifications shall be referred to the 10 by 10 cm image size.

Digitization - Images shall be digitized to 512 by 512 by 12 bits at a maximum rate of 8 frames per second.

Frame Integration - The ability to digitally integrate up to 512 individual frames shall be provideJ.

Image Storage - The ability to store up to three (3) consecutive integrated frames for real time display shall be provided. During a scan these three images shall be continuously updated so that the most recent three (3) images are present in memory. Storage of a fourth image for display and comparison shall be provided. Provision for flicker image display of any two stored images shall be included.

Turntable Rotation - Rotation of the turntable shall be paused or halted at the control of the operator or inspector. Images in memory shall be available for inspection. Images already stored shall be recallable for comparison.

Image Feature Highlighting - Provision shall be made to control a computer generated arrow, circle or other symbol to mark the location of an image feature of interest. Such overlays shall not affect the data in the image, but shall be stored along with the image for review purposes.

Image Display - The image display shall be by high resolution monitor capable of a minimum 720 by 680 lines by 256 grey levels. Window and level controls shall be included.

Image Manipulation - The following image manipulation shall be provided:

1) X-Y translation,
2) Region of interest average value, standard deviation and number of pixels,
3) Histogram,
4) Region of interest magnification and histogram,
5) Edge enhancement [specify method(s)],
6) Image subtraction (including image weighted subtraction),
7) Noise filtering,
8) Windowing and level control.

Auxiliary Image Presentation - Auxiliary image presentation and review capability shall be provided. The auxiliary system shall have the full complement of image manipulation functions.

Alignment - A mirror in the beam path shall be provided along with both a laser source for alignment and a flood source for defining the field of view.

Laser Alignment Procedure - A procedure shall be devised to allow the alignment of the source with the detector and to align the center of the image field with the desired point of inspection of the motor. A television viewing system for this purpose shall be provided.

Beam Collimation - A mechanical aperture to limit the X-ray field and minimize scatter shall be provided for the betatron.

X-Ray Film Compatibility - The system will be so designed that X-ray film cassettes may be readily accommodated.

Betatron Mechanical System Upgrade - The Betatron cabling shall be improved by provision of an additional support cable in order to limit stress on these components during the frequent vertical motion that will occur during an X-ray scan of a motor.

3.1.2.2 *Motor Turntable Platform*

A turntable onto which the solid rocket motors may be mounted for inspection by the RTR system shall be provided. The turntable shall be mounted on a small motor given flanged wheel car that travels along a set of rails embedded in the floor of the facility. These rails run from one end of the facility out the main entry doors and into a large bay where motors brought into the facility are stored temporarily.

Turntable Load Capability Requirements - The turntable must accommodate a load of at least 15,000 pounds with no loss of performance.

Stopped Motion - Rotation of the rocket motor shall be stopped during data collection. Angular steps shall be synchronized with the number of frames selected to be integrated.

Stepping Speed - Angular speed during stepping shall be maximized but consistent with the angular momentum of the motor and the desire for safe and stable operation.

Accuracy of Alignment - The motor shall be positionable on the turntable such that its axis is within plus or minus 1 cm of the axis of rotation of the turntable.

3.1.3 RTR Equipment Description. The equipment shall be powered by 120 V or 240 V, single phase 60 Hz as appropriate. Controls for operating the Betatron are provided by the radiographic facility, but the supplier is responsible for integrating these controls into the RTR system. The Supplier shall provide the RTR system, subsystems and supporting equipment described in the following itemization as part of the total RTR system.

1) A complete RTR camera system including all necessary radiation shielding and appropriate cooling for noise reduction, with internal optical focusing capability, X-ray conversion screen and optical magnification of 2X and any other subsystems required to meet the performance specifications defined above.

2) Complete control and recording capability including image storage and processing, optical disc image recording and playback, image manipulation, frame integration, and high resolution display.

3) Complete Examination programming and control, including, step size, number of frames for integration, vertical positioning and vertical step size, system alignment and positioning, and integration of the Betatron position control with the RTR Camera and motor location. All basic set-up and operation functions shall be integrated with a menu driven computer program for operator ease of use.

4) Complete Auxiliary motor inspection review console, including digital image playback, high resolution display and image manipulation.

5) Rocket motor supporting turntable mounted on an electric motor driven rail car with stepping motor control or other means of achieving angular resolution of 1 degree plus or minus 0.5 degrees.

6) All equipment necessary to achieve system alignment, including in-beam mirror, laser and flood light sources, auxiliary adjustable source aperture, TV viewing system, and any other required equipment.

7) All necessary auxiliary equipment including power supplies, cables, adapters fasteners, means of providing additional support to the Betatron control and power cables, and any other necessary parts and supplies.

3.1.4 Construction and Installation. All equipment, procedures, calculations, and materials shall be provided to accomplish the following:

Shielding - Appropriate shielding shall be provided as required for the RTR camera.

Scatter Reduction - A remotely operated mechanical aperture system shall be installed at the Betatron to limit the beam to the area of the RTR camera and to reduce scatter. If appropriate, additional shielding to reduce scattering from the facility wall directly behind the RTR camera may be installed.

Turntable - The turntable may be mounted on an existing rail car if appropriate. The existing rail car has mounted on it a horizontal belt system for rotation of the motors. This equipment could be removed and the turntable installed.

Betatron Integration and Optimization - The Betatron has multi-axis motion capability. It traverses along the vertical axis and rotates about this axis in the horizontal plane. It also rotates in a vertical plane from an angle above horizontal to 90 degrees below horizontal. Advantage of this capability may be taken in order to optimize the geometry of the RTR and to provide easier access to the RTR camera and to the motor. These motions are controlled from the radiographic facility, but control could be relocated to the control room if desired.

Camera Location - The RTR camera may be mounted either on the turntable or separately. If the latter approach is used the drive mechanism for the rail car would require modification to achieve the positioning accuracy desired. Use of film must be accommodated, hence the RTR camera must be either removable or positionable in a location that will not obstruct the use of X-ray film.

3.1.5 Operation.

Elements of equipment design and construction, together with applicable operating routines and procedures, shall combine to promote simple, straightforward, repeatable equipment utilization. The equipment shall be routinely set up, operated, diagnosed and maintained by personnel with normal NDT-technician training.

The system shall operate reliably in a sheltered area under the following conditions:

Ambient Air Temperature, 60 °F to 100 °F
Relative Humidity, 5 percent to 90 percent
Rocket motor temperature, 32 °F to 100 °F

Explosion Proofing. The equipment shall be designed to be explosion proof with respect to the hazards associated with solid, non-volatile rocket propellant.

Equipment operation shall not be affected by unscheduled power outages or other electrical upsets. The System should recover from power failures with a minimum of operator intervention, but should be in a stand-by mode pending an operators command to continue.

3.2 Ancillary Motor Handling Equipment

3.2.1 General Configuration

The radiographic facility is of modest size. (See the attached facility floor plan and equipment configuration.) Entry for the introduction of rocket motors is via an electrically driven rail car on which motors are mounted horizontally and which enter the facility from one end through a ten foot high door. The change to vertical must be effected in the radiography facility. This shall be done using additional cranes mounted just inside the entry. The motors will be lifted from the first transport car, raised to the vertical position and placed on the second car. The second car will have installed on it the turntable. The vertically mounted motor will be transported to the RTR location in the vertical configuration by the rail car and its integral turntable. The existing

equipment consists of a rail car on which is mounted a belt system used to rotate motors in the horizontal configuration.

Overhead cranes shall be mounted inside the radiography facility at the entrance, in a configuration that optimizes the repositioning of the motors and maximizes the safety of this operation. It is anticipated that two cranes will be required. These overhead cranes shall not interfere with the normal operation of the existing overhead crane. Lifting of the motors shall be via a special fixture provided by the manufacturer of the motors.

3.2.2 Design Construction and Operation

Cranes shall have a load capacity of 20,000 pounds.

Cranes used to lift and manipulate motors will be so designed to minimize the possibility of mishandling; i.e., crane motion will be restricted to open areas.

Equipment shall be powered by 240 V, 60 Hz single phase AC.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 Preliminary Concept Review

Within 30 days after contract award, the supplier shall present to the procuring agency a review, at the supplier's facility, or the proposed Real Time Radiography concept. The review shall include sufficient quantitative detail to permit the procuring agency and the supplier to jointly assess the likelihood of satisfactory equipment performance.

4.2 Design Review

Approximately 120 days after contract award, the supplier shall present to the procuring agency a review at the supplier's facility of the design of the Real Time Radiography System. The review shall include quantitative details of the design, experimental and calculational verification of the achievement of the performance requirements, and such other quantitative design information necessary to allow the procuring agency to assess the expected equipment performance. In particular the algorithms to be used for edge enhancement and other image manipulations shall be described in detail.

4.3 Compliance Testing

The supplier shall carry out tests demonstrating that the RTR system meets the performance specifications of paragraph 3.1.1 above. The supplier is responsible for the fulfillment of all inspection and compliance testing specified below. These inspections and compliance tests, at the option of the procuring agency, may be witnessed by a representative of the procuring agency.

4.3.1 Pre-Delivery Compliance Testing. It is desirable for this test to be carried out prior to delivery and installation. This test need not include the turntable or indexing capability and may be done using any X-ray source that is or can be filtered to be approximately equivalent to the Betatron.

Only those parts of paragraph 3.1.1.1 pertinent to the operation of the camera and the generation of images need to be considered.

Image manipulation and image storage and retrieval shall be demonstrated at the supplier's facility.

Sufficient data shall be generated and delivered to the procuring agency in accordance with DI-T-1906 to support a decision on compliance with the applicable portions of 3.1.1 above.

4.3.2 Government Acceptance Compliance Testing and Inspection. The Real Time Radiographic System including the Betatron upgrades and add-on's, turntable and indexing system, ancillary motor handling cranes and equipment shall be installed at the U.S. Army Depot Activity, Pueblo, Colorado. The equipment shall be operated by the supplier to examine a P-II solid-propellant rocket motor (or section thereof). Sufficient data shall be generated and provided to the procuring agency in accordance with DI-T-1906 to support a decision on full compliance with all the performance requirements of paragraph 3.1.1.

In addition, the use of the auxiliary motor-handling cranes and equipment shall be demonstrated.

4.3.3 Rejection and Retest. Equipment that has been rejected may be reworked or have parts replaced to correct defects, and then be resubmitted for inspection testing for compliance. Full particulars shall be provided concerning the corrective action taken.

4.4 Certification

The equipment shall be certified by the supplier to be explosionproof, with respect to the hazards associated with solid, nonvolatile rocket propellant.

4.5 Warranty

The equipment shall be warranted by the supplier to be free of defects in materials and workmanship for one (1) year from the date of acceptance by the procuring agency.

5.0 DOCUMENTATION

5.1 Test Data

All pertinent test data related to verifying compliance with the performance requirement of 3.1.1 above as required in 4.3 above shall be delivered to the procuring agency.

5.2 Supporting Documentation

The supplier shall provide the RTR System and Sub-system Operating instruction, Calibration Procedures, Maintenance Instructions, Electrical Schematics, Turntable Assembly Drawings, and Parts Lists in accordance with DI-M-5406A. The required documents are described below.

5.2.1 RTR System and Subsystems Operating Instructions. A separately bound Operating Instructions Manual shall be provided at delivery of the System. The Operating Instructions Manual shall provide general and specific information on the normal modes of operation of the system in the form of a tutorial. It shall include instructions on system set-up, modes of operation, and all

procedures needed for system alignment, indexing, calibration, and image storage and recall. A separate section shall provide detailed information on the use of the advanced and special features of the system. The Operating Instruction Manual shall include a detailed section on the use and functioning of the image enhancement and manipulation features of the system.

5.2.2 RTR System and Subsystems Maintenance and Repair Manual. A separate System and Subsystems Maintenance and Repair Manual shall be provided at delivery of the system. This manual shall contain all the information required for routine maintenance of the system and subsystem. It shall contain electrical schematics and parts lists of the RTR System including the Turntable and its Subassemblies, and contain Assembly Drawings of the Turntable and its drive and indexing mechanisms. The Maintenance and Repair Manual shall contain a listing of anticipated fault functions and their symptoms, and recommended repair procedure.

5.2.3 Operating and Maintenance Manual for Motor Handling Equipment. A separately bound Operating and Maintenance Manual for Motor Handling equipment shall be provided at delivery of the System. This manual shall contain operating and general maintenance instructions for the overhead cranes installed in the radiographic facility.

6.0 SUPPORT

The supplier shall develop and supply as part of his proposal a specific plan to support the procuring agency in the following areas:

6.1 System Maintenance

The supplier shall provide for routine maintenance for the first year of operation of the system after acceptance. This shall include but is not limited to the electrical and mechanical components of the system, computer hardware and system software, and desirable or required system improvements. The supplier shall demonstrate his commitment to providing service, repair and replacement of critical parts for the life of the equipment. This required maintenance does not include the Betatron.

6.2 Technical Support

The supplier shall provide technical support to the system operators at U.S. Army Pueblo Depot activity. Technical support shall consist of rapid response to technical questions or difficulties in the set-up or operation of the system that require the input or knowledge of the system designer. Technical support in the optimum use of the system for inspection of items other than the Pershing II Rocket Motor shall be provided. This technical support shall be available on an on-call and rapid response basis for one year following the acceptance of the equipment. A minimum of five (5) on-site visits by appropriate contractor personnel shall be provided during the technical support period.

The supplier shall demonstrate his commitment to providing long-term technical support on an as-needed basis.

6.3 Training of Operators

The supplier shall develop and administer a formal operator training program. The program shall be of the "hands on" type and shall provide the operators direct experience in the operation of the system. Included in the training shall be general use of the system including set-up, real-time inspection, image storage, and image manipulation.

7.0 OTHER CONSIDERATIONS

7.1 Bidders Conference

A bidders conference will be held on [insert date] at the U.S. Army Pueblo Depot Activity for the purpose of giving bidders an opportunity to review the facility and the Betatron, and to be given an opportunity to observe a typical solid propellant motor.

Attendance at the bidders conference is restricted to U.S. citizens only.

7.2 Teaming

Teaming as a means of optimizing the achievement of these requirements is encouraged.

QUALITY ASSURANCE PROVISIONS
REAL TIME RADIOGRAPHIC SYSTEM

1. Inspection. Inspection of supplies purchased under this contract shall be performed by the contractor in accordance with FAR 52.246-1, Contractor Inspection System Requirements.

2. Government Inspection/Acceptance. Inspection and Acceptance shall be performed by the Government at destination and shall be based on successful demonstration of the equipment's ability to meet the requirements of the Contract Statement of Work utilizing a 1st Stage Pershing Rocket Motor or section of same at the choice of the Government. Also the contractor shall supply the penetrometer described in section 3.1.1.1 which shall be used in conjunction with the above motor or section thereof as part of the test procedures using the criteria. The government reserves the right to use a penetrometer of it own design to determine compliance.

Document Summary List

1. DI-T-1906 Seq. No. 1	Compliance Test and Demonstration Reports	15 Dec 69 Cat 2
2. DI-M-5406A Seq. No. 2	Commercial Data	8 Jun 82 Cat 1

APPENDIX C:

BORESCOPE SYSTEM SPECIFICATION

1.0 SCOPE

This specification describes the characteristics of a borescope system for the thorough examination of propellant surfaces inside solid-propellant rocket motors.

2.0 APPLICABLE DOCUMENTS

Drawing 11503333-079, sheets 2 and 3

Drawing 11503519-089, sheets 2 and 3

US Army Missile R and D Command,
Redstone Arsenal, Alabama

3.0 REQUIREMENTS

3.1 Equipment Performance.

The equipment shall be designed and fabricated to perform its intended functions reliably and efficiently, as they are described below. These functions are to be performed on the interior of a loaded solid-propellant rocket motor which is mounted for easy access with its axis horizontal, and approximately 54 inches from the floor.

Entry into the motor can be accomplished from either end. The nozzle assembly will be in place during the equipment set-up and operation. The rocket motor can be rotated about its axis continuously and in either direction during equipment set-up and operation. The general configuration of the rocket motor is shown in Figure 1.

3.1.1 Engagement. The probe component of the equipment shall be able to gain access to the areas requiring inspection, as shown in Figure 1. Physical proximity to the propellant surfaces in these areas shall be adequate for purposes of illumination and image gathering in support of the thorough inspection objective.

3.1.2 Field of View. The field of view presented to the operator on an external color video monitor shall be large enough to permit complete surface inspection in a reasonable period of time. The field of view shall contain sufficient detail to support the consistent detection of cracks as small as 0.003 inches in width.

3.1.3 Image Quality. The resultant image presented to the operator on an external color video monitor shall integrate the elements of illumination, magnification, resolution, contrast and stability to support the consistent detection of cracks as small as 0.003 inches in width.

3.1.4 Data Generation. The equipment shall support the generation of data, if required by the operator, in three modes:

1. The dimensions of a surface feature displayed on the video monitor shall be directly determinable to within 10% or 0.10 inches, whichever is larger.

2. The location of a surface feature displayed on the video monitor shall be easily determinable to within 1.0 inches.

3. The capability shall exist for recording the color video image in a continuous manner.

3.2 Design, Construction, Operation.

3.2.1 General. Elements of equipment design and construction, together with applicable operating routines and procedures, shall combine to promote simple, straightforward, repeatable equipment utilization. The equipment shall be routinely set up, operated, diagnosed and maintained by trained personnel with normal NDT-technician capability.

3.2.2 Electrical. The probe component of the equipment shall be enclosed in a continuous conductive sheath (e.g., stainless steel), which will be suitably connected to the rocket motor grounding points during insertion and operation. This sheath may be breached for optical purposes at the distal end. No voltages will exist between any element of the probe, internal or external, and the conductive sheath during insertion and operation.

3.2.3 Thermal. The entire probe component of the equipment shall be maintained at a temperature or temperatures not in excess of 150 deg. F during operation. It is to be assumed that the airflow through or around the rocket motor is negligible, and that the temperature of the rocket motor itself is less than 100 deg. F.

3.2.4 Mechanical. The probe component of the equipment shall not touch the surface of the propellant during insertion, operation or removal, nor shall any auxiliary equipment including the operator. The equipment shall not contact any portion of the rocket motor except for mounting or stability purposes, and these contacts shall involve only the forward port ring, normally used for igniter mounting, and the forward and aft skirt rings.

3.2.5 Electromagnetic Compatibility. The equipment shall not produce significant electromagnetic interference, such as would interfere with the normal operation of standard NDT inspection equipment or related electrical/electronic devices or instruments. The equipment shall not be adversely affected by the electromagnetic environment present in a normal NDT inspection facility. The operating area will not include any active high voltage discharge or X-ray equipment, or magnetic pulse generators which could interfere with the proper operation of video recording equipment.

3.2.6 Explosion Proofing. The equipment shall be designed and constructed to be explosion proof with respect to the hazards associated with solid, non-volatile rocket propellant.

3.2.7 Self-Test/Calibration. Means shall be provided, or procedures defined, to allow the occasional ration of the feature size measuring capability and the feature locating capability.

3.2.8 Operating Environment. The equipment shall be designed to operate in a sheltered area under the following conditions:

Ambient air temperature: 60 deg. F to 100 deg. F.

Relative humidity: 5% to 95%.

Rocket motor temperature: 32 deg. F to 100 deg. F.

Dust: Normal inspection area conditions.

The equipment shall be powered by 120 V, 60 Hz a.c., 20 amperes, maximum. The power and equipment necessary to rotate the horizontal rocket motor will be provided by the test facility, not by the borescope supplier. The power and equipment necessary to insert and retract the borescope probe shall be provided by the borescope supplier.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 Preliminary Design Review.

Within a specified time period of contract initiation, the supplier shall present to the procuring agency a review of the proposed equipment design. The review shall include sufficient quantitative detail to permit the procuring agency and the supplier to jointly assess the likelihood of satisfactory equipment performance, as well as cost and schedule compliance.

4.2 Responsibility for Inspection.

The supplier is responsible for the fulfillment of all inspection requirements specified below.

4.3 Equipment Inspections.

Two inspections shall be performed by the supplier. These inspections may, at the option of the procuring agency, be witnessed by a representative of the procuring agency.

4.3.1 Pre-Delivery Inspection. The equipment design, construction, and operation shall be reviewed for compliance with 3.0 above. This inspection shall take place at a facility chosen by the supplier, prior to release for delivery to the procuring agency. Sufficient data shall be generated and delivered to the procuring agency to support a decision on compliance with 3.0 above.

4.3.2 Acceptance Inspection. The equipment shall be installed by the supplier at the NDT facility, US Army Depot Activity, Pueblo, Colorado. The equipment shall be operated by the supplier to examine a portion of the interior of a solid-propellant rocket motor. Sufficient data shall be generated to support a decision on compliance with 3.0 above.

4.3.3 Rejection and Retest. Equipment which has been rejected may be reworked or have parts replaced to correct defects, and then be resubmitted for inspection. Full particulars shall be provided concerning the corrective action taken.

4.4 Certification.

The equipment shall be certified by the supplier to be explosion proof, with respect to the hazards associated with solid, non-volatile rocket propellant.

4.5 Warranty.

The equipment shall be warranted by the supplier to be free of defects in materials and workmanship for one year from the date of acceptance by the procuring agency.

5.0 DOCUMENTATION

5.1 Data.

All pertinent data, related to performance and testing and verifying compliance with 3.0 above, shall be delivered to the procuring agency.

5.2 Supporting Documentation.

The following documents shall be provided:
1. Operating instructions.
2. Maintenance instructions.
3. Electrical schematics.
4. Parts lists.

APPENDIX D:

ULTRASONIC THICKNESS GAGE FOR PERSHING-II NDI

Background

A thickness gage is required for inspection of the aluminum skirts of the first and second stage of the Pershing-II. The general characteristics of the required system are that it be a simple hand held portable unit with a digital readout and a means of calibration. An off-the-shelf instrument is desired; therefore no instrument development is anticipated under this procurement. However, minimal modifications that can be applied to a standard instrument in order for it to meet the specifications below would be acceptable. The minimum specifications of the required instrument are given in the following.

Specifications

THICKNESS MEASUREMENTS

Thickness range: 0.010 inches to 1.00 inches of aluminum

Resolution: 0.0001 inch

Repeatability: 0.0002 inch

Accuracy: Greater of +0.0005 inch or + 1% of thickness

Temperature Stability: +0.001 inch 50 F to 95 F

Battery Voltage Stability: +0.0002 inch over the battery discharge operating range

CALIBRATION

Automatic Two Point Calibration Mode

Two precision four-point step gages shall be supplied, viz:
Material No. 1: D6AC Steel
Material No. 2: 2014-T6 Aluminum

ELECTRICAL

Power: Rechargeable NiCd Batteries
Operable from battery charger/adapter

Operating Time: 8 hours following 16-hour battery charge
12 hours with full charge

DISPLAY

Hand Held High Contrast LCD or equivalent

OPERATING CHECKS AND FAULT DISPLAYS

No echo - out of range or no coupling
Battery low - 1 hour of operating time available
Systems of units - English or Metric if available

ENVIRONMENTAL

Temperature Range: Storage -35 °F to 120 °F
Operating 25 °F to 105 °F
Dust and Moisture resistant

OTHER REQUIREMENTS

Unit must have ability to operate over a wide velocity range that includes most metals and plastics.

Velocity Range - 2000 to 8000 meters per second

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